Characterization of a dc plasma torch by pressure measurements: analytical models and experiments

Vincent Rat, Jean-François Coudert

Characterization of a dc plasma torch by pressure measurements : analytical models and experiments

V. Rat and J.F. Coudert

SPCTS-CNRS-UMR6638, University of Limoges, France

Abstract *:* The aim of this contribution is to propose an analytical model to describe dc plasma torch properties at the nozzle exit from experimental data. This simplified approach attempts to highlight the influence of experimental parameters on plasma jet velocity and pressure contributions. The plasma inside the anode-nozzle is considered as stationary and is divided into the arc column and a surrounding cold layer which electrically insulates the plasma from the nozzle wall. Heat conduction is evaluated by using Kirchoff's potential, which is described, as it is done also for the electrical conductivity, as a function of the gas specific enthalpy instead of temperature. The model is used to calculate the specific enthalpy radial distribution. From that, and by introducing a mean isentropic coefficient, it is possible to calculate the axial velocity of the plasma jet at the nozzle exit and to evaluate the different pressure contributions. The comparison between predicted and previously measured plasma jet velocities shows good agreement for various experimental conditions.

Keywords: dc plasma torch, pressure measurements, plasma velocity, isentropic exponent

1. Introduction

A dc (direct current) plasma spray torch is used as an enthalpy and momentum source to melt and spray refractory powders onto a substrate. A high current electric arc (typically between 300 and 600 A), is blown into a cylindrical anode-nozzle, producing a thermal plasma with a high level of specific enthalpy [1]. Despite the fact that the torch is power supplied with a current regulated source, the arc jet such produced presents unsteady characteristics which are mainly due to the motion of the arc in the nozzle channel. From an experimental point of view, the stationary behaviour of the torch can be fully described by defining time averaged quantities such as the mean voltage, the thermal losses in the cooling circuits, the thermal torch efficiency and the specific enthalpy of the plasma jet. The thermal losses at the electrodes ascribed to convection, radiation and electron condensation usually represent 35 up to 50 % of the power input. These losses allow knowing the energy left within the plasma jet, at the nozzle exit, useful for powder treatments.

This contribution, which is based to a large extent on reference [2], proposes an analytical model to describe dc plasma torch properties at the nozzle exit from experimental data such as specific enthalpy, mean voltage, arc current intensity, nozzle diameter and thermophysical properties of plasma forming gases. In a previous study, it has been shown that thermal losses and the mean electric field can be satisfactorily predicted [3]. This simplified approach attempts to highlight the influence of experimental parameters on plasma jet velocity and pressure contributions. This can be helpful for practical purposes to increase or decrease the plasma jet velocity following the chemical composition of the injected powders for example. In order to model the plasma flow, it is assumed that the real plasma flow, at the exit of the nozzle, is the same as an isentropic plasma flow which would be generated from a reservoir. It is then required to introduce an averaged isentropic exponent which is a characteristic depending on thermophysical properties of the plasma. The measurements of pressure and the operating parameters will allow deducing the value of the isentropic exponent of the plasma.

2. Contribution of pressure in anode nozzle

In this section, we attempt to find the pressure variation between the nozzle exit (at atmospheric pressure) and a point located on the gas feeding line upstream the plasma torch. Four different pressure contributions can be identified:

- the overpressure,. ΔP_f, due to the cold gas flow between the measurement point in the gas feeding line and the arc region,
- the isentropic overpressure, ΔP_{is}, which is the driving pressure. It is the same as that produced by an isentropic flow with a mean reservoir specific enthalpy $\overline{h}$ equivalent to that really observed,
- the overpressure, ΔP_v, due to the plasma viscosity within the nozzle. It will be admitted that it is proportional to the nozzle length ℓ,
- the magnetic overpressure ΔP_m due to the Maecker effect [4].

The reservoir pressure can easily be obtained by using the energy conservation of an isentropic flow and assuming that a small fraction of the specific enthalpy is converted into kinetic energy. This assumption can be readily validated by checking $\bar{u}^2 / 2\bar{h} << 1$.

Thus, the isentropic overpressure, $\Delta P_{is} = P_0 - P_a$, has the following form:

$$\Delta P_{is} = \frac{\bar{h}\dot{m}^2(\gamma - 1)}{2\gamma S^2 P_a} \qquad (1)$$

where $\bar{h}$, $\dot{m}$, γ, S and P_a are the mean specific enthalpy, the total gas mass flow rate, the isentropic exponent, the area of section at the nozzle exit and the atmospheric pressure.

Two different ways have been tested to describe the viscous overpressure ΔP_v. First, the viscous pressure ΔP_v is described as a linear loss pressure proportional to the nozzle length ℓ. It can be written:

$$\Delta P_v = \frac{\alpha\ell}{2}\rho u^2 \qquad (2)$$

where α, u and ρ are respectively the linear loss pressure coefficient, the velocity and density of the plasma.

Equation (2) can also be written [2]:

$$\Delta P_v = \alpha\ell.\Delta P_{is} \qquad (3)$$

Second, assuming a simple Poiseuille flow at the nozzle exit, the viscous overpressure term can be also written;

$$\Delta P_v = \frac{128\bar{\nu}\dot{m}\ell}{\pi d^4} \qquad (4)$$

where $\bar{\nu}$ and d are respectively the kinematic viscosity and the internal nozzle diameter.

The magnetic overpressure ΔP_m will be deduced after measurements as it will be shown below.

Finally, the total pressure measured P_t can be written :

$$P_t = P_a + \Delta P_f + \Delta P_{is} + \Delta P_v + \Delta P_m \qquad (5)$$

3. Experimental conditions

All measurements are performed at atmospheric pressure using a home-made plasma torch equipped with a standard cylindrical anode nozzle. The plasma mixture is argon-hydrogen used with three different volume flow rates keeping constant the molar ratio argon/hydrogen.

The measurements of pressure are performed for a current intensity ranging between 350 and 600 A for the three different volume flow rates and the different anode nozzle diameters (see Table 1). The pressure is measured by using a piezoresistive pressure transmitter Keller (PAA21) which is mounted on the plasma gases feeding line. The averaged values of the torch voltages, the current intensities, the thermal losses at the electrodes of the plasma torch are also measured.

Calculated maximum axial velocity at the nozzle exit will be compared in the following with measurements of plasma jets velocities previously performed [8,9]. For experimental parameters concerning plasma jet velocity measurements, the internal nozzle diameters are 6, 7, 8, and 10 mm, the arc current varies between 400 and 600 A for an Ar-H_2 plasma (45-15 slm).

Table 1 : Experimental parameters- Anode nozzle characteristics where d and ℓ are respectively the inner diameter and the length of the cylindrical nozzle, arc current intensity and flow rates of plasma gases.

	Anode name	d(mm)	ℓ (mm)
Anode characteristics	A1	5	62.7
	A1'	5	32.7
	A2	5.1	32.7
	A3	6	33.4
	A4	7	34.9
Current Intensity (A)	350 up to 600		
Plasma gas (Ar-H_2) (slm)	30/10	60/30	45/15

4. Results and discussion

4.1 Pressure contributions and isentropic exponent

The sum (P_a+ΔP_f) is obtained by measuring pressure for the different mass flow rates and internal nozzle diameter without generating the plasma discharge (I = 0).

If $\Delta P_p = P_t-(P_a+\Delta P_f)$, equation (5) is written:

$$\Delta P_p = \Delta P_m + \frac{\gamma - 1}{2\gamma}\frac{\dot{m}^2\bar{h}}{P_a S^2}(1+\alpha\ell) \qquad (6)$$

Equation (6) yields a linear relationship between the measured overpressure, ΔP_p, and the term $\dot{m}^2\bar{h}$ which is known from experimental parameters. Figure 1 represents the dependence of ΔP_p on $\dot{m}^2\bar{h}$ for experimental conditions gathered together in Table 1. The accuracy of measurements is $\pm 2\ 10^3$ Pa. It can be seen that the linear relationship is confirmed following the different internal nozzle diameters. At fixed propulsive force, represented by the term $\dot{m}^2\bar{h}$, the pressure variation logically increases as the internal nozzle diameter decreases. Moreover, the ordinate, when the term $\dot{m}^2\bar{h}$ vanishes, gives the magnetic overpressure ΔP_m. These values corresponding to 5, 6 and 7 mm nozzle diameters respectively are 1, 8 and

4.10^3 Pa and with an accuracy of $\pm 3.10^3$ Pa. These values are not sufficiently reliable to be interpreted as a function of diameter or arc current intensity. However, it has to be noted that the mean measurement, 6.10^3 Pa, is consistent with the value given by Gauvin [5] for transferred arcs, namely 2.5 .10^3 Pa.

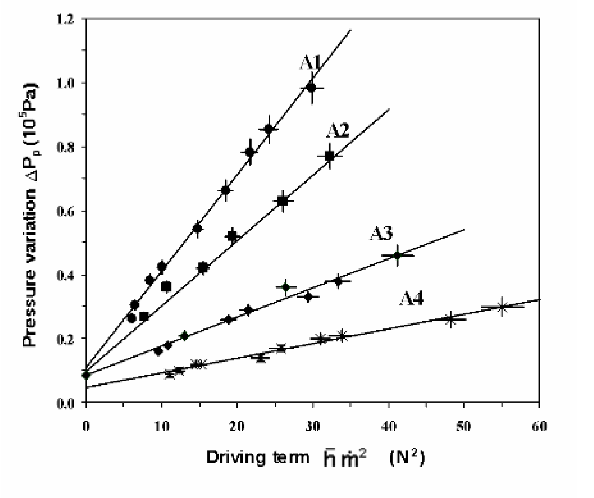

Fig. 1 Pressure variation $\Delta P_p = P_t - (P_a + \Delta P_f)$ as function of the product $\bar{h}\,\dot{m}^2$ where P_t, P_a and ΔP_f are respectively the total pressure, the atmospheric pressure and the loss pressure due to the plasma gases, and where $\dot{m}$ and $\bar{h}$ are respectively the mass flow rates of gases and the specific enthalpy measured for experimental conditions given by Table 1 and for the different anodes A1, A2, A3 and A4.

The linear loss pressure coefficient α can be found by using two different nozzle lengths with the same inner nozzle diameters (A1 and A1' in Table 1) and operating at identical experimental conditions to assume the same isentropic exponents.
Using equation (6), it is found that α is 16.1 ± 2.0 m^{-1}.
Considering the Poiseuille flow, it can be written:

$$(\Delta P_p - \Delta P_m) = \frac{128\bar{\nu}}{\pi}\frac{\dot{m}\,\ell}{d^4} + \frac{\gamma - 1}{2\gamma}\frac{16\dot{m}^2\bar{h}}{P_a\pi^2 d^4} \tag{7}$$

We can define an non-dimensional pressure ΔP_r such as:

$$\Delta P_r = \left(\Delta P_p - \Delta P_m\right) \Big/ \frac{16\dot{m}^2\bar{h}}{P_a\pi^2 d^4} \tag{8}$$

that is

$$\Delta P_r = \frac{\gamma - 1}{2\gamma} + 8\pi\bar{\nu}\frac{\ell P_a}{\bar{h}\dot{m}} \tag{9}$$

Figure 2 shows the dependence of ΔP_r on the experimentally determined term $Z = \ell P_a / \bar{h}\,\dot{m}$. The linear evolution is confirmed. The ordinate when the parameter Z vanishes is 0.069 corresponding to a γ value of 1.16. The slope of the linear regression gives $\bar{\nu}$ =5.5 10^{-3} m^{2}s^{-1} which is consistent with experimental conditions.
Equation (7) contains the proportionality relationship between the isentropic overpressure and the term $\frac{16\dot{m}^2\bar{h}}{P_a\pi^2 d^4}$, it can be written:

$$\Delta P_{is} = (\Delta P_p - \Delta P_m - \frac{128\bar{\nu}}{\pi}\frac{\dot{m}\,\ell}{d^4}) = \frac{\gamma - 1}{2\gamma}\frac{16\dot{m}^2\bar{h}}{P_a\pi^2 d^4} \tag{10}$$

Figure 3 shows the evolution of ΔP_{is} as a function of $16\dot{m}\bar{h}/P_a\pi^2 d^4$ for the different experimental conditions reported in Table 1 for the Ar-H_2 plasmas. The linear variation is again confirmed and the value of the slope, (γ-1)/2γ, allows determining the isentropic exponent. Following the accuracy of measurements, the isentropic exponent is found to vary between 1.15 and 1.19. This value is consistent to that of Burm *et al.* [6] who recommends 1.16 for plasmas with ionisation degree higher than 5%.

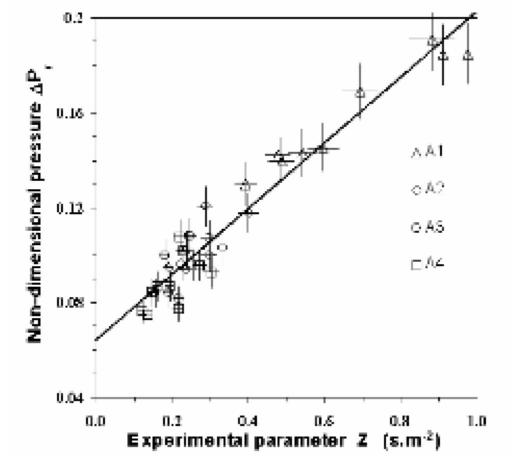

Fig. 2 Non-dimensional pressure ΔP_r as function of the parameter $Z = \ell Pa / \bar{h}\,\dot{m}$ (see equation 29) for different experimental conditions reported in Table 2. A1, A2, A3, A4 represents respectively the anodes names given in Table 2

4.2. Plasma jet velocity and model validation

This section presents a comparison between previous plasma jet velocity measurements and calculated plasma jet velocity following the preceding models.
On the one hand, maximum plasma jet velocities were measured [7,8] using an optical method based on the propagation of the plasma jet luminosity fluctuations.
On the other hand, the plasma velocity at the nozzle exit can be evaluated following the value of the isentropic exponent determined above. A mean value of 1.17 will be taken for an Ar-H_2 (75-25%vol) considered in plasma velocities measurements.
It can be shown that plasma velocity at the nozzle exit can be written [2]:

$$u(r) = v^* \left(\sqrt{1 + \frac{2h(r)}{v^{*2}}} - 1 \right) \tag{11}$$

where $v^* = \frac{\gamma}{\gamma - 1} \frac{P_a S}{\dot{m}}$, h(r) the specific enthalpy radial profile.

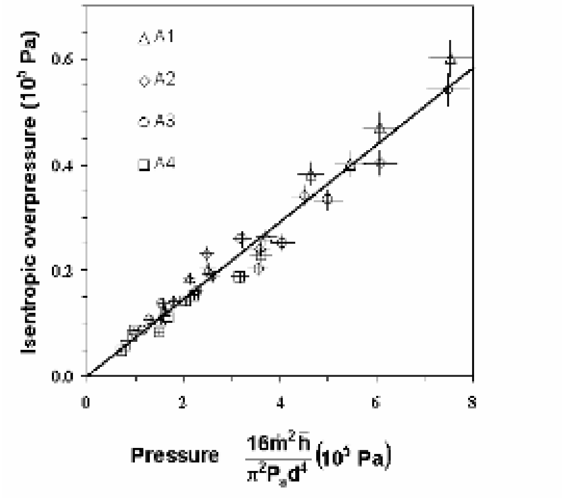

Fig. 3 Dependence of isentropic pressure ΔP_{is} on experimental operating conditions (see Table 2).

The maximum plasma velocity, u_{max}, is defined such as:

$$u_{max} = v^* \left(\sqrt{1 + \frac{2h(0)}{v^{*2}}} - 1 \right) \tag{12}$$

with $h(0) = h_c + \Delta h$.

The quantities h_c and Δh take into account experimental parameters and thermophysical properties of considered gases [2].The results given by equation (12) are then compared in Figure 4 with measurements reported in references [8,9]. These measurements were performed using an Ar-H_2 (75-25%vol) and for different internal nozzle diameters d, namely 6, 7, 8 and 10 mm.

Good agreement is observed in Figure 4 between simplified calculations (equation (12)) and measurements performed over a wide range of experimental conditions which validates the simplifed approach of the plasma flow description.

5. Conclusion

A simplified analytical model has been constructed, and describes the plasma flow at the nozzle exit of a dc plasma torch operating at atmospheric pressure. It is based on a two-layer assumption for the plasma jet at the nozzle exit. It allows defining an electrical conduction threshold and the corresponding critical specific enthalpy h_c which depends upon thermophysical properties of plasma forming gases used. Specific enthalpy profiles at the nozzle exit can be deduced from experimental data, such as torch voltage, arc current, flow rate of plasma gases, torch thermal efficiency, nozzle diameter and chemical composition of plasma gases. The maximum value of the specific enthalpy profile (h_c+Δh), obtained from experimental data, is used in an analytical relationship derived for plasma velocity. It also involves an averaged isentropic exponent γ which is evaluated from the determination of pressure contributions acting within the plasma torch. The total pressure is measured upstream of the plasma torch on the gas feeding line. The average value 1.17 of the isentropic exponent obtained for the Ar-H_2 plasma here is found and is consistent with that found in the literature and appears to be a key parameter in the plasma jet velocity.

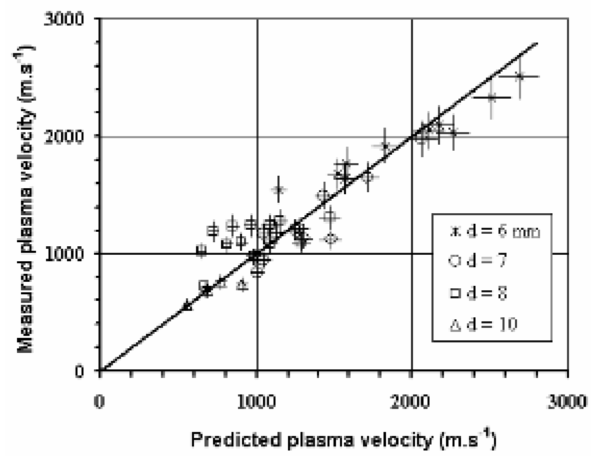

Fig.4 Comparison between measurements [7,8] of the maximum plasma jet velocity at the nozzle exit of a dc plasma torch for different inner nozzle diameters, d, i.e. 6, 7, 8 and 10 mm (Ar-H2, 45/15 %vol) and its calculation in the same conditions following the present model including plasma properties through the critical specific enthalpy h_c and the isentropic coefficient.

[1] Boulos MI, Fauchais P, and Pfender E 1994 *Thermal Plasmas: Fundamentals and Application* **1**, New York,(Plenum).

[2] V. Rat and J.F. Coudert, J.Phys. D: Appl. Phys. **39**, 4799 (2006).

[3] J.F. Coudert, C. Chazelas, D. Rigot, V. Rat *J. High Temp. Mat. Process.* **9**, 173 (2005)

[4] H. Meacker, *Zeitschrift für Physik* **141,** 198 (1955)

[5] W.H. Gauvin *Plasma Chem. Plasma Process.* **9**, 65S (1989)

[6] K.T.A.L. Burm, W.J. Goedheer and D.C. Schram *Physics of Plasmas* **6**, 2622 (1999)

[7] J.F. Coudert, M.P. Planche and P. Fauchais *Plasma Chem. Plasma Process.* **15**, 47 (1995)

[8] M.P. Planche, J.F. Coudert and P. Fauchais *Plasma Chem. Plasma Process.* **18**, 263 (1998)

[9] M.P. Planche *PhD. Thesis*, University of Limoges (1995)- in french